Plant Characteristic Measurement System

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Plant Characteristic Measurement System

Field

The present invention relates to a plant characteristic measurement system and to an associated method. The plant characteristic measurement system may use measurements of the reflectance of a plant, for example obtained using an imaging array. The plant characteristic may for example be health or ripeness.

Background

Conventional colour imaging relies on the collection of light by a sensor which is selectively sensitive to three colours of light (red, blue, green). A similar mechanism for colour perception is used by the human eye, which has cones which are preferentially sensitive to a particular colour of light, each colour having a particular wavelength.

Multispectral imaging often supplements these three bands of colour sensitivity with additional bands of light or radiation sensitivity, either within the visible range, or at wavelengths beyond those perceptible to the human eye, such as, for example, infra-red and ultra-violet. Furthermore, multispectral imaging may permit a closer separation in wavelength of detected radiation. For example, the visible spectrum may be split into a greater number of wavelength ranges than the three typically used in colour imaging.

Multispectral images can be collected by filtering radiation with band-pass filters, each filter having a transmission wavelength centred at a predetermined wavelength, and passing the filtered radiation to a sensor. A different filter can be used to allow a single sensor to record the intensity of radiation at each particular wavelength.

Hyperspectral imaging measures detected radiation at each wavelength over a range of wavelengths (divisions between detected wavelengths being finely spaced). This permits the use of subtle variations in the relative intensity of radiation at particular wavelengths within the electromagnetic spectrum to extract potentially useful information. For example, hyperspectral imaging may permit the reconstruction of a full wavelength spectrum of each pixel of a captured image.

Hyperspectral imaging typically involves the use of a refractive or diffractive element to split broad-spectrum radiation into its component parts, with the angle at which radiation is refracted/diffracted being dependent on the particular wavelength. With this approach, an array of sensors or pixels can be used, each sensor or pixel collecting information relating to the intensity of radiation at a particular wavelength. The spectrum of radiation can then be reconstructed for each pixel in the image.

However, the use of complex optical components to split and filter radiation can be expensive. Furthermore, where reflectance is being considered, the characteristics of the radiation source used must play a part in the analysis of data. For example, sunlight does not have a flat spectrum, with significant differences in radiation intensities across the visible (and IR/UV) spectrum. Some of these variations may be as a result of different solar emission intensities at different wavelengths, while others may result from specific atmospheric absorptions at certain wavelengths. Where a white light (broad spectrum) source is used, then by collecting a hyperspectral image of the light reflected from an article, the reflectance at each wavelength can be assessed. However, the intensity of incident light at each wavelength must also be known, so that a specific reflectance can be calculated. Some such techniques may also require that the sample is subjected to a high intensity light source, which can be problematic when the sample is light sensitive.

Summary

According to a first aspect of the invention there is provided a plant characteristic measurement system comprising, a first radiation source configured to emit radiation at a first radiation wavelength and a second radiation source configured to emit radiation at a second radiation wavelength, a detector configured to detect radiation at the first radiation wavelength and at the second radiation wavelength, the detector comprising a two-dimensional imaging array, a controller configured to control the first and second radiation sources and the detector to detect radiation reflected by the a plant specimen when it is irradiated by the first and second radiation sources at the first and second radiation wavelengths, and a processor configured to calculate an indicator of the plant characteristic based upon detected images of radiation reflected by the plant specimen at each of the first and second radiation wavelengths.

The indicator of the plant characteristic may be a two-dimensional array of plant characteristic indicator values.

The indicator of the plant characteristic may be a spectral vegetation index.

The spectral vegetation index may be Normalised Difference Vegetation Index or Photochemical Reflectance Index.

The first and the second radiation sources may comprise light emitting diodes or laser diodes.

The first radiation source, the second radiation source, the detector, the controller and the processor may be arranged as a single unit.

The single unit may be a handheld device.

The plant characteristic measurement system may further comprise a first device and a detachable module wherein the detector may form part of the first device and wherein the first radiation source and the second radiation source may form part of the detachable module.

The first device may be a mobile telephone, a digital camera or a tablet computer.

The processor may be within the first device or within the detachable module. The controller may comprise a set of computer readable instructions arranged to be read and executed by the processor, which cause the processor to control the first and second radiation sources and the detector. Alternatively, the controller may comprise a second processor, the second processor being within the detachable module.

The controller may be arranged to cause the plant characteristic measurement system to irradiate the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and to detect a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength, and to calculate an indicator of the plant characteristic based upon the plurality of detected images.

The controller may be arranged to cause the plant characteristic measurement system to irradiate the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and to detect a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength, and to calculate a plurality of indicators of the plant characteristic based upon the plurality of detected images.

The plurality of images may be a temporal sequence of images with a predetermined separation in time.

The plant characteristic may be plant health or ripeness.

According to a second aspect of the invention there is provided a method of measuring a characteristic of a plant specimen, the method comprising, irradiating the plant specimen with radiation at a first radiation wavelength, detecting an image of radiation reflected by the plant specimen at the first radiation wavelength, irradiating the plant specimen with radiation at a second radiation wavelength, detecting an image of radiation reflected by the plant specimen at the second radiation wavelength, and calculating an indicator of the plant characteristic based upon the detected images.

The indicator of the plant characteristic may be a two-dimensional array of plant characteristic indicator values.

The indicator of the plant characteristic may be a spectral vegetation index.

The spectral vegetation index may be Normalised Difference Vegetation Index or Photochemical Reflectance Index.

The method of measuring the characteristic of a plant specimen may further comprise comparing the indicator of the plant characteristic with a threshold value.

The method of measuring the characteristic of a plant specimen may further comprise irradiating the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and detecting a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength, and calculating an indicator of the plant characteristic based upon the plurality of detected images.

The method of measuring the characteristic of a plant specimen may further comprise irradiating the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and detecting a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength and calculating a respective plurality of indicators of the plant characteristic based upon the plurality of detected images.

The plurality of images may be a temporal sequence of images with a predetermined separation in time.

It will be appreciated that aspects of the invention can be implemented in any convenient form. For example, the invention may be implemented by appropriate computer programs which may be carried on appropriate carrier media which may be tangible carrier media (e.g. disks) or intangible carrier media (e.g. communications signals). Aspects of the invention may also be implemented using suitable apparatus which may take the form of programmable computers running computer programs arranged to implement the invention.

It will be appreciated that where features are discussed in the context of one aspect they may be applied to other aspects.

Description

An embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 schematically shows a plant characteristic measurement system according to an embodiment of the invention;

Figure 2 is a Photochemical Reflectance Index (PRI) map obtained using an embodiment of the invention;

Figure 3 is a graph which shows PRI values of pixels of the PRI map of Figure 2;

Figures 4, 5 and 6 show experimental data obtained using an embodiment of the invention;

Figure 7 is an image obtained using an embodiment of the invention;

Figure 8 is a graph which shows experimental data extracted from the image of Figure 7;

Figure 9 is an image obtained using an embodiment of the invention;

Figures 10A and 10B are images which show experimental data extracted from the image of Figure 9 ;

Figure 11 is a graph which shows experimental data extracted from the images of Figures 10A and 10B;

Figure 12A and 12B are images of part of the region shown in the image of Figure 9;

Figure 13 is a graph which shows experimental data extracted from the images shown in Figures 12A and 12B.

Figure 14 is an image of a different part of the region shown in the image of Figure 9;

Figure 15 is a graph which shows experimental data extracted from the image shown in Figure 14;

Figure 16A is a graph which shows experimental data extracted from parts of the image shown in Figure 9;

Figure 16B is a graph which shows experimental data extracted from parts of the image shown in Figure 9; and

Figure 17A and 17B are images obtained for visual comparison with experimental data shown in Figures 9 to 16B.

Embodiments of the invention direct radiation with two or more different wavelengths at a plant, and detect the intensity of radiation reflected from the plant at those wavelengths (e.g. using an imaging array). A measure of the health of the plant is then determined based on the measured intensity of the reflected radiation.

A number of spectral vegetative indices have been developed which make use of the relationship between the reflectance of a crop at different wavelengths and the health of that crop.

One such example of a spectral vegetative index is the Normalised Difference Vegetation Index (NDVI). NDVI is calculated according to the ratio of reflectance at two predetermined wavelengths, 800 nm and 670 nm, as shown in the equation below:

$$NDVI = \frac{R_{800} - R_{670}}{R_{800} + R_{670}} \qquad (1)$$

where:

R_{800} is the reflectance at 800 nm, and
R_{670} is the reflectance at 670 nm.

In the case of NDVI, the reflection of infra-red radiation from a plant leaf at 800 nm and the reflection of radiation at 670 nm are both considered. The reflection of radiation at 670 nm depends upon the absorption due to Chlorophyll in the plant leaf, whereas the reflection at 800 nm is substantially unaffected by Chlorophyll in the plant leaf. NDVI is calculated as the difference between the reflectances at both wavelengths divided by the sum of the reflectances. Any change in the intensity of the reflected radiation at 670 nm, due to increased or decreased Chlorophyll activity in the plant leaf, will be expressed as a change in NDVI.

Chlorophyll activity can be taken to be an indicator of plant health (which may be considered to be an example of a plant characteristic). NDVI can therefore be used as an indirect indicator of plant heath. A plant may exhibit reduced chlorophyll activity in reaction to a stress to which it is exposed, such as drought. Furthermore, an indicator such as NDVI may be suitable for use as an early stress indicator, providing a valuable early indication that a plant is being subjected to stress before symptoms of that stress are clearly visible to the human eye.

For NDVI measurements, the measurement at 800 nm may be relatively insensitive to wavelength variation. The 800 nm measurement is used to determine the background infra-red plant leaf reflectivity, and this background reflectivity may be relatively constant over a range of wavelengths. For example, a wavelength in the wavelength range 800-950 nm may be used.

A further example of a spectral vegetative index, Photochemical Reflectance Index (PRI), makes use of the reflectance of vegetation at 542 nm and 571 nm to assess the health of a plant. PRI is calculated by comparing the difference and sum of reflectances of the plant at 542 nm and 571 nm:

$$PRI = \frac{R_{542} - R_{571}}{R_{542} + R_{571}} \qquad (2)$$

where:

R_{542} is the reflectance at 542 nm, and
R_{571} is the reflectance at 571 nm.

PRI is used as a method to investigate the xanthophyll cycle in plants. The xanthophyll cycle is the conversion of violaxanthin into antheraxanthin and zeaxanthin. This conversion is used as a method of dissipating excess energy from photosynthesis. Changes in the PRI response of plants can be used to measure the dissipation of excess energy by plants. Changes in the PRI response of plants have also been linked with other sources of stress, such as drought. Under drought conditions, the threshold of light required before production of antheraxanthin and zeaxanthin begins may be reduced, providing an indication of drought stress.

The xanthophyll cycle is triggered in response to excess light. Therefore, PRI measurements may be taken shortly after a specimen has been exposed to bright lighting conditions, such as, for example, direct mid-day sun light, for sufficient time to allow the xanthophyll cycle to reach equilibrium.

PRI measurements may be taken in shielded conditions, i.e. out of direct sunlight. This can be achieved by shielding the specimen to be imaged from direct light, for example using an operator’s hand to create a shadow.

Figure 1 shows schematically a plant characteristic measurement system 1 according an embodiment of the present invention. A controller 2 controls a first source of radiation 3 and a second source of radiation 4. Each source of radiation (3,4) may be a narrow band radiation source configured to emit radiation at a different wavelength. The controller 2 also controls a detector 5. The system 1 may be positioned adjacent to a specimen 6 to be imaged. The specimen may be a plant or a leaf of a plant. The system 1 may be positioned for example such that it obtains an image of a leaf of a plant.

In operation, the controller 2 may cause a first source of radiation 3 to irradiate the specimen 6 with a narrow band of radiation centred at a first wavelength. While the specimen 6 is being irradiated by the first source of radiation, the controller 2 may cause the detector to measure the intensity of radiation incident upon the detector 5 (thus detecting radiation centred at the first wavelength which has been reflected by the specimen). The controller 2 may then cause the second source of radiation 4 to irradiate the specimen 6 with a narrow band of radiation centred at a second wavelength. While the specimen 6 is being irradiated by the second source of radiation, the controller 2 may cause the detector to measure the intensity of radiation incident upon the detector 5 (thus detecting radiation centred at the second wavelength which has been reflected by the specimen).

The detector 5 measures the intensity of radiation incident upon it as a result of irradiating the specimen with each of the first source of radiation 3 and the second source of radiation 4.

Provided that the first and second sources of radiation 3, 4 are located adjacent to one another, and the orientation of each with respect to both the specimen and the detector 5 is similar, the path of radiation from each source of radiation to the specimen 6 will be similar. Therefore, the proportion of radiation emitted by each source 3, 4 reaching the specimen 6 will be similar (if the first and second radiation sources emit radiation at similar intensities). It can thus be approximated that the intensity of incident radiation at the specimen will be similar for radiation originating from each of the radiation sources 3, 4. This allows a measurement of the radiation incident upon the detector 5 to be used as a measure of the radiation reflected by the specimen 6, and a comparison to be made between the reflectance of the specimen at each of the wavelengths of the emitted radiation.

The detector 5 and sources of radiation 3, 4 may be arranged such that the radiation emitted by the sources of radiation 3, 4 is not directly incident upon the detector 5. The sources of radiation may be oriented away from the detector, or at least not oriented towards the detector. A screen (not shown) may be positioned between the sources of radiation 3, 4 and the detector 5 to prevent radiation travelling directly from the radiation sources to the detector.

The radiation sources 3, 4 may be configured such that they emit radiation with the same or similar intensities as each other (e.g. by selecting appropriate sources and supplying appropriate amounts of power to them). This allows a straightforward comparison to be made between the measured intensities of reflected radiation without needing to include a measurement of the emitted radiation. The intensity of the radiation sources may also be initially calibrated to take into account the wavelength sensitivity of the detector.

In an alternative embodiment, the radiation sources may have different intensities. If this is the case then the measured intensity of reflected radiation can be adjusted to take account of the differences between the radiation sources.

It is possible to calculate the reflectance of an object by measuring both the power of incident radiation and the power of reflected radiation, the relationship being as shown in equation (3):

$$R = \frac{P_R}{P_I} \tag{3}$$

where:

R is the reflectance,
P_R is the reflected power intensity, and
P_I is the incident power intensity.

True reflectance cannot be measured without an accurate measure of the radiation incident upon the specimen and the area of the specimen, as well as the area of the detector. However, if the intensity of radiation emitted by two sources of radiation are known to be the same, and they are proximate to one another, then it will be understood that an assumption can be made that these parameters do not change between two sources of radiation. Consequently, a measure of the intensity of reflected radiation can serve as a measure of reflectance, provided that its use is only in comparison with another similarly derived measure of reflectance. In this way, it is possible to compare the reflectance, or relative reflectance, of radiation from several sources of radiation by a single specimen. The term “reflectance” as used in this document encompasses a measure of reflectance derived in this way, and is not limited to a strict measure of the proportion of optical power reflected by a specimen.

In the embodiment illustrated in figure 1, the two sources of radiation 3, 4 may be narrow band sources. For example, the sources of radiation may be laser diodes (LDs) or light emitting diodes (LEDs), each being configured to emit radiation at a wavelength of interest. For example, a first LED or LD may be configured to emit radiation at 542 nm and a second LED may or LD may be configured to emit radiation at 571 nm (to allow a measurement of PRI). Alternatively, a first LED or LD may be configured to emit radiation at 670 nm and a second LED or LD may be configured to emit radiation at 800 nm (to allow a measurement of NDVI). In other embodiments, LEDs or LDs may be configured to emit at other wavelengths in order to allow other spectral vegetative indices to be measured. LEDs or LDs which emit any suitable combination of wavelengths may be used. LEDs or LDs are advantageous because they are inexpensive and provide monochromatic radiation. However, other radiation sources which provide monochromatic radiation may be used (although these may be more expensive).

Lenses or other optical elements may be used in conjunction with the radiation source to focus, collimate or in some other way direct the radiation emitted by the sources towards the specimen which is to be imaged.

It may be desirable to use a plurality of LEDs or lasers to achieve a desired level of incident optical power. If a plurality of LEDs or lasers is used to create a single source of radiation, then a diffusing sheet may be used in the radiation path to diffuse the output of the individual sources of radiation. Alternatively, a diffusing sheet may be used in conjunction with a single LED or other radiation source (e.g. to modify the output of that radiation source to make it more diffuse). This may be done for example to modify the output of that radiation source to make it more similar to the output of the other radiation source.

The detector 5 is a two-dimensional imaging array, and may for example be any kind of photo-detector such as, for example, a charge coupled device (CCD), a CMOS image sensor, or any other suitable imaging sensor. The detector may further comprise one or more lenses and/or filters. The detector may be a detector (camera) which is integrated into a mobile telephone or hand-held computing device such as a tablet computer. The detector may be a compact digital camera. The detector may for example have of the order of a million pixels or more, e.g. around 10 million pixels (which may be expressed as 10 mega-pixels).

The use of a lens or lenses to focus radiation onto the detector 5 allows the detector 5 to form an image. This is advantageous over the scenario where there is no lens, and consequently no image formed as the use of a two-dimensional imaging array without any focusing means would result in a blurred image. Each pixel within a two-dimensional array would instead capture radiation from all directions, rather than from a specific point, which would be detrimental to image quality and would increase the image noise level.

The radiation sources 3, 4 and detector 5 may be arranged as a single unit. This unit may be configured to be hand-held. A standard mobile telephone may be adapted to function as the plant characteristic measurement system via the addition of suitable radiation sources. For example, in the case of a mobile telephone, a detachable module including the radiation sources 3, 4 may be configured such that it can be attached to the mobile telephone. The module may be securely attached to the mobile telephone such that the orientation of the module relative to the mobile telephone cannot be modified when it is attached. This may help to ensure that the radiation sources 3, 4 have a desired orientation relative to the detector. A processor in the mobile telephone may act as a controller which controls the radiation sources 3, 4. The processor may synchronise operation of the radiation sources 3, 4 and the detector 5.

Operation of the processor in this regard may be controlled by appropriate software. The radiation source module may be electrically connected to the mobile telephone. This may allow control of the radiation sources by the processor, and may also allow power to be delivered to the radiation sources from the battery of the mobile telephone. Alternatively, the processor may be connected to the radiation sources using a wireless connection, such as Bluetooth. A separate battery may be provided for the radiation sources. The processor of the mobile telephone may also perform the analysis of the imaging data recorded by the detector.

In an alternative embodiment, a camera (e.g. a compact camera) may be used instead of a mobile telephone to form the unit with the radiation sources. The camera may include a processor which can be programmed to act as a controller and thereby control the radiation sources and to perform calculations such as difference calculations and curve fitting. This embodiment may include other features referred to above in connection with the mobile telephone embodiment.

In an alternative embodiment, a tablet computer may be used instead of a mobile telephone to form the unit with the radiation sources. The tablet computer may include a processor which can be programmed to act as a controller and thereby control the radiation sources and to perform calculations such as difference calculations and curve fitting. This embodiment may include other features referred to above in connection with the mobile telephone embodiment.

In a yet further alternative embodiment, the radiation sources and detector may be arranged as a single unit with the processor which can be programmed to act as a controller and thereby control the radiation sources and to perform calculations such as difference calculations and curve fitting. This embodiment may include other features referred to above in connection with the mobile telephone embodiment.

The unit may include a USB socket.

The system of figure 1 may be arranged to measure the spectral vegetative index known as NDVI, in which the reflection of infra-red radiation from a plant leaf at 800 nm is compared with the reflection at 670 nm (absorption due to Chlorophyll occurring at 670 nm). In this example, the first source of radiation 3 may exclusively emit radiation at the wavelength of 800 nm, while the second source of radiation 4 may exclusively emit radiation at the wavelength of 670nm.

It will be appreciated that where radiation wavelengths are discussed, wavelength ranges may vary between applications. For example, a radiation source which is suitable for use in NDVI measurements may emit radiation in a band of 800-950 nm. Furthermore, such a radiation source may be treated as though it exclusively emits radiation at 800 nm for the purposes of that measurement. This is because it is common for the reflectance of most plant specimens to be relatively flat across the 800-950 nm range. If a finer degree of wavelength selectivity is required, the radiation sources 3, 4 may be configured to emit a narrow band of radiation wavelengths. In the case of PRI measurements, a FWHM of around 10 nm centred at a test wavelength of 542 or 571 nm may be used. Other FWHM may be used for PRI measurements or other measurements.

In one measurement cycle, measurements may be taken (in no particular order) with:

(1) no radiation from either of the first or second radiation sources,
(2) radiation from only the first radiation source, and
(3) radiation from only the second radiation source.

The measurements may be controlled by the processor referred to further above.

An initial measurement with no radiation sources active may be used as a measure of the background radiation intensity and may be subtracted from the subsequent measurements.

The measured reflected radiation intensity at each radiation wavelength, measured sequentially, can be used to calculate a measure of NDVI or PRI, as shown in equation 1 or 2 respectively.

It will be appreciated that while the above example refers to individual measurements, each measurement is in fact an image obtained by the imaging array. Each pixel of the image represents the intensity of incident radiation at that point in the image. The difference and sum calculations referred to further above may be performed for each pixel, thereby providing an image which is for example an NDVI or PRI image (i.e. each pixel of the image represents an NDVI or PRI value). This NDVI or PRI image may be used to obtain information about the health of a plant. This may be on the basis of a statistical analysis of the pixels (e.g. as described further below in connection with figure 3). Alternatively or additionally, the analysis may be of the spatial arrangement of the pixels of the image.

A plurality of images may be obtained using the system, following which these images can be combined in a variety of ways. For example, 30 images may be taken using a 1 second exposure time from a conventional mobile telephone camera. Thus, for each measurement (1), (2) and (3) referred to above, 10 images are obtained. These images, if combined together, can produce a single image with an effective exposure time of 10 seconds for each measurement. This effectively increases the sensitivity of the detector, and may help to remove measurement noise.

Embodiments of the invention may allow plant health (or other plant characteristics) to be measured using a low cost system which may be hand-held. The system may comprise a mobile telephone to which radiation sources are attached, or may comprise a compact camera to which radiation sources are attached. The system may allow images which show a spectral vegetative index to be obtained, thereby providing large amounts of data which may be used to measure plant health (or other characteristics). Image analysis may yield information regarding plant health (e.g. the presence of disease or damage caused by pests). Alternatively, statistical analysis of pixels of the image may yield information regarding plant health (or other characteristics).

Figure 2 shows a PRI image created from an image of a tomato plant obtained using a Cannon EOS 1100D camera (the image being inverted for printing purposes). Images were obtained using illumination from an array of LEDs emitting at 570nm and 532nm. Horizontal and vertical axes are provided to illustrate the number of pixels in each dimension. The image shown comprises 4272 horizontal pixels and 2848 vertical pixels, resulting in 12,166,656 pixels in total. The brightness of each pixel represents a PRI value for that pixel of the image. As can be seen from scale bar the PRI values range from –0.2 to 0.4. However, it will be appreciated that PRI values can take any value between -1 and +1. In the image shown in figure 2, any pixel with a recorded intensity value below a predetermined threshold (e.g.50 out of 255 in the case of figure 2) has been excluded from the PRI calculation. Any such pixel has been set to a minimum value in the image and is not considered in further analysis. This is done to exclude from the PRI calculation regions of the image which do not show plant matter or have a shadow cast upon them.

Figure 3 shows a line plot representing the number of pixels of each PRI value in the image of figure 2. It can be seen from figure 3 that a majority of pixels fall within a narrow range (PRI = 0-0.1).

The histogram of PRI values can be used to differentiate between areas of interest. For example, the PRI histogram may show multiple peaks, relating to different features. Curves may be fitted to the peaks, with the centre of each peak taken as a representative PRI value for that feature. For example, soil, which may be in the background when imaging a plant in a field, may be excluded from a PRI measurement in this way.

A similar technique to that described above with reference to PRI can be used to measure NDVI or other spectral vegetative indices.

By use of the system described above, it is possible to replace the broad-spectrum radiation source typically required for hyperspectral imaging with monochromatic radiation sources. Consequently, complex wavelength selective filtering may be avoided. In an embodiment of the invention, only radiation at the wavelengths of the radiation sources will be incident upon the specimen of interest. Therefore, only those wavelengths will be reflected. This enables the reflectivity at those wavelengths to be readily calculated. If the intensity of the radiation source and the sensitivity of the detector are known for each wavelength, then it is possible to access hyperspectral information without the need for complex and expensive optical components transforming the reflected image.

The use of a system in which only radiation at the wavelengths of the radiation sources is incident upon the specimen of interest, reduces the heating effect of broad-spectrum radiation. A significant majority of the radiation emitted by a broad-spectrum radiation source, and subsequently incident upon a specimen of interest, will not contribute usefully to a measurement of reflectance which is required for the measurement of a particular spectral vegetative index. As such, any such out-of-band radiation incident upon the specimen of interest will serve only to heat the specimen.

Information relating to reflected intensity at specific wavelengths can be used to compare the reflectivity at those wavelengths, rather than examining raw spectral information (which is more costly to obtain and to analyse). A system according to an embodiment of the invention may for example be provided with radiation sources which only emit radiation at wavelengths used to obtain a particular measurement (e.g. 670 nm and 800 nm or 542 nm and 571 nm). The system may thus be cheaper to manufacture and easier to operate. As mentioned further above, the system may include a mobile telephone with a camera, which may be relatively cheap and easily sourced.

To exemplify the method of using the system described above, an experimental study has been carried out, the results from which are now described.

Ten maize plants and ten tomato plants were grown from seed. Plants were divided into a control group (5 plants) and a test group (5 plants). During early growth all plants were watered sufficiently to be well established.

From a predetermined point in time (36 days) water was restricted to the test group of plants. The control group continued to have adequate water provided. NDVI measurements were taken for each plant on each day. As the test group of plants became drought stressed, the NDVI of the test plants was monitored with reference to the NDVI of the healthy control group of plants. The NDVI was obtained by photographing the plant using a Cannon EOS 1100D camera, and performing the fitting described above in relation to figure 3.

Figure 4 shows a plot of the NVDI values measured for the 10 tomato plants for several days after water restrictions were applied to the test group. Each error bar represents the range of NDVI values recorded for individual plants, with the central value for each day being the mean of these values. Squares show the data collected from the control group, whereas circles represent the test group of plants.

A mean NDVI value for healthy (control group) plants is plotted as a horizontal line. Standard deviations from this line are also plotted. A plant specimen may be considered stressed when the measured NDVI falls below the second standard deviation from the mean.

It can be seen that four days after water restrictions were applied to the test group, the NDVI of both sets of plants begins to decline. However, the NDVI decline in the test plants is significantly greater than that observed in the control plants. A large range of values can be seen in some tests sets, such as the test group NDVI result on five days after water restrictions were applied.

Where these individual results are considered in detail, the range of values can be explained. Figure 5 shows the NDVI values collected for just the test group of plants, with each plant being shown by a different shaped symbol. Whereas the results of most days show a close grouping, five days after water restrictions were applied shows four plants with a similar (low) NDVI and one (healthy) outlier. In this case, the plant responsible for the outlying result took one day longer to respond to the drought stress than the other plants. On subsequent days, it can be seen to be within the close grouping of the other plants of the test group.

Now considering figure 6, similar results are shown for a maize crop. It can be seen from this set of results that a clear decline in NDVI occurs 10 days after water restrictions were applied. Figure 6 clearly shows the close grouping of NDVI values observed for maize test plants throughout the stressing period.

The speed of response of the measurement to a stress stimulus (removal of water) within 10 days for maize compares favourably with other measurement techniques. The measurement method may thus be suitable for use as an early indication of plant being under some kind of stress.

In use, the system may be hand held, or may be mounted underneath a vehicle, such as a tractor. In either use scenario, the system may be oriented such that it can image plant leaf matter in preference to plant stem matter. For example, when mounted underneath a vehicle, the system may have a top down orientation. This will be advantageous because it is within the leaves that photosynthesis occurs, and therefore is in the leaf of the plant that NDVI is most sensitive to changes in behaviour.

The collection of large images (e.g. a million or more pixels per image) allows large amounts of NDVI or PRI data to be obtained quickly and easily, compared with the case if for example a photodiode or other non-imaging detector were to be used. Imaging arrays having around 10 million pixels or more are widely available in consumer devices such as mobile phones. Embodiments of the invention may use such imaging arrays. The large amounts of data obtained may be treated as a collection of discrete point measurements, allowing sums or averages which provide improved measurement accuracy (and which may reduce measurement noise).

In an embodiment, a single radiation source may be used instead of two radiation sources. For example, the single radiation source may be configured to first emit radiation at a first wavelength and then subsequently emit radiation at a second wavelength.

In an embodiment, a radiation source of the system may be configured to generate radiation over a range of wavelengths and may include a filter which only transmits a desired wavelength. For example a narrow band radiation source may be created by use of a broad-spectrum radiation source used in conjunction with a narrow band band-pass filter, or monochromator. A disadvantage of this arrangement is that power is used to generate radiation which is not used for measurements, thereby depleting a power supply more quickly.

Obtaining images such as NDVI or PRI images allows the identification of image features which may be characteristic of a plant health problem, such as a particular disease.

To exemplify a further method of using the system described above, a further experimental study has been carried out, the results from which are now described. In this study a first maize plant was treated with the nonspecific herbicide paraquat, while a second maize plant was left without paraquat treatment. NDVI images of the two maize plants were then compared. An NDVI image of the first (treated) maize plant is shown as the left hand leaf in Figure 7. An NDVI image of the second (untreated) maize plant is shown as the right hand leaf in Figure 7. The leaf of the plant treated with paraquat has a lower average NDVI in response to the herbicide. In addition to the lower average NDVI values, there are regions of the treated leaf with noticeably lower NDVI where the herbicide spray contacted the leaf. These can be seen in Figure 7 as lighter patches on the left hand leaf.

Figure 8 shows the histogram of NDVI values for the data shown in Figure 7. The histogram can be seen to contain 3 distinct peaks. The first peak is at ~0.25 and is related to the areas damaged by the paraquat spray. The second peak is at ~0.44 and is related to the test (treated) plant leaf, in the regions which were not directly damaged by the spray. The third peak at ~0.52 and represents the healthy (untreated) control leaf.

The localised values of the spectral vegetative indices for various leaf features or regions can be used to highlight or identify regions of interest, such as leaf damage, or regions of stress.

Image processing techniques can be applied to captured hyper-spectral, or spectral vegetative index, images. Such techniques can be used to obtain information relating to, or to identify, characteristic features of a particular stress from the images of individual plant leaves.

In addition to the use of single images to assess plant health (or other characteristics), a temporal series of images of the same specimen can be captured over time, allowing a comparison to be made at different times. The series of images can be inspected to assess the evolution of image characteristics which for example indicate plant health. Characteristics of the images which are of particular interest are the shape of, or the rate of change of the shape of particular features which are caused by a source of stress to the plant. An interval of several minutes may be a suitable time between images. An interval of one hour may be a suitable time between images (e.g. when monitoring for damage caused by herbicides or insects). An interval of one day may be a suitable time between images (e.g. when monitoring for the effects of drought).

The effects of the herbicide paraquat on maize plants was also investigated over a period of time after application. As above, NDVI was used as the index being indicative of plant health.

In preparation for the experiment, six hours prior to an initial image being taken, the maize plants were prepared by being sprayed with paraquat. A dose equivalent to 400 grams of paraquat diluted in 200 litres of water per hectare was used. Plants which had been treated, and control plants which had not been treated were then positioned and secured in a test location so that a series of images could be compared without having to make adjustments for image orientation or field of view. The test location was kept under constant ambient illumination.

A modified Cannon EOS 1100D digital single lens reflex (DSLR) camera was again used to acquire the images. Illumination was provided by LEDs which emitted at 670 nm and 810 nm. The camera had been modified by removal of the infra-red blocking filter, so as to allow the detector to receive and capture near infra-red light. The camera and light sources were set-up so that images could be taken with each of the test leaves of the plants lying parallel to the camera's field of view.

Figure 9 shows an example of one of the images taken using the illumination of a 670 nm LED. Four leaves are shown lying across the image. A first test leaf 10 is a leaf, to which paraquat has been applied. A first control leaf 11 is a leaf which has had no paraquat applied. A second test leaf 12 is a further test leaf, to which paraquat has been applied. A second control leaf 13 is a further control leaf, which has had no paraquat applied.

After a series of calibration images taken using a grey image card at the same position as the plants were placed, images were recorded according to the imaging sequence outlined above. The imaging sequence was then repeated at 5 minute intervals for a time of 15 hours and 45 minutes. A total of 190 sets of sets of images were produced over the period of observation of the experiment, with each of the 190 sets of images producing a map of the NDVI value and a histogram of the NDVI values within that map.

Figure 10A shows an NDVI map produced for the investigated plants at the start of the period of observation showing the same field of view as captured in Figure 9. The NDVI data has been inverted for clarity in reproduction.

Figure 10B: shows an NDVI map produced for the investigated plants at the end of the period of observation. The NDVI data has been inverted for clarity in reproduction.

A comparison between the start NDVI map (Figure 10A) and the end NDVI map (Figure 10B) reveals the changes across the period of observation. In particular, there are several regions of lower NDVI which have developed during the period of observation. For example, test leaf 10 can be seen to contain several regions of damage 14, 15 which are more pronounced in Figure 10B than in Figure 10A, showing the effect of paraquat over the period of observation.

Instead of considering just the detail of a region of damage, a histogram can be produced showing the NDVI value for each pixel in the NDVI map. Figure 11 shows such a histogram of NDVI values for test leaf 10 both at the start of the observation period (as shown in figure 10A) and at the end of the observation period (as shown in Figure 10B). It can be seen that the main peak in NDVI values has shifted to a lower value or approximately 0.50 (previously 0.55). In addition, the main peak in the histogram has become broader, exhibiting a full width half maximum (FWHM) of 0.097 (previously 0.087).

In addition, Figure 11 allows an estimate to be made of the total number of damaged pixels (each of which corresponds to a predetermined area of the plant specimen) at each time. For example, if it is determined that a value of NDVI below a certain threshold is indicative of leaf damage, then the number of pixels which satisfy this criteria can be calculated from NDVI maps (e.g. Figures 10A, 10B), or from a histogram of NDVI values (e.g. Figure 11). In this embodiment, a damage threshold is chosen to be an NDVI value of 0.4, with any pixel having an NDVI value of less than 0.4 being classified as damaged. It is clear from Figure 11 that a larger number of pixels fall into this category at the end of the observation period than at the start of the observation period. In fact, only a small number of healthy pixels, as shown in Figure 10A, exhibit an NDVI value below 0.4, and as such, the contribution to the measure of damaged pixels from healthy pixels is minimal.

This number of damaged pixels can further be understood by looking at the spatial coordinates of each region of damage. Figure 12A shows a damage map of a region of the test leaf 10 at the start of the observation period in which any pixel for which the corresponding NDVI value is less than 0.4 is shown in white (1), and any pixel for which the corresponding NDVI value is greater than or equal to 0.4 is shown in black (0). While there are some regions visible in white, these largely relate to a shadow cast by the leaf, and can be disregarded as an experimental artefact.

Figure 12B shows a damage map of the same region of the test leaf 10 as shown in figure 12A but now at the end of the observation period. Figure 12B shows several regions of leaf damage which are not visible in Figure 12A, which have developed over the course of the observation period.

Figure 13 shows a summary of the damaged leaf area (number of damaged pixels) of the test leaf 10, as determined by the method described above, as the observation period progresses.

Initially the number of damaged pixels is approximately 50000, which remains approximately constant for a period of 200 minutes. However, from 200 minutes until the end of the observation period, at around 950 minutes, the number of damaged pixels increases approximately linearly. The number of pixels categorized as damaged increases by almost 100% during the period of observation.

Figure 14 shows a damage map of a region of the control leaf 11, highlighting all pixels which have an NDVI value below 0.4. The damage map of Figure 14 represents the damage at the beginning of the observation period.

Figure 15 shows a summary of the damaged leaf area (number of damaged pixels) of the control leaf 11, as determined by the method described above, as the observation period progresses. It can be seen that the area of the leaf that falls within this range of NDVI values does not increase in the same way as seen with test leaf 10. The number of damaged pixels remains approximately constant at 25000 pixels throughout the entire observation period.

Having considered the NDVI values for entire leaf regions, more attention was given to particular regions of interest within a particular leaf. Two such regions were selected from each of test leaf 10 and control leaf 11. The first region of test leaf 10 is a region exhibiting visible paraquat damage, which will be referred to as t2d. The second region of test leaf 10 is a region which is relatively undamaged, which will be referred to as t2u.

The first region of control leaf 11 is a region exhibiting some physical damage, or bruising, which will be referred to as c2b. The region c2b can be seen in Figure 14, approximately corresponding to coordinates (400,300)-(600,400) where a significant number of pixels are highlighted. The other significant feature in this image is the highlighted region at the lower edge of the leaf, which corresponds to a shadow cast by the leaf, and can be disregarded as an experimental artefact. The second region of control leaf 11 is a region which is relatively undamaged, with a high NDVI value, and will be referred to as c2h.

A histogram of NDVI values was plotted for each pixel within each of the four sample regions, for each of the series of measurements. The NDVI value which appears most frequently in each histogram, and the width of the peak fitted to the histogram was then estimated. This NDVI value which appears most frequently can be taken to represent the average (mode) NDVI value for the region to which the respective histogram relates. This average NDVI value was then plotted as a function of time across the period of observation for each sample region. Figure 16A shows the evolution of the average NDVI values for each of the sample regions.

The full width half maximum (FWHM) of each NDVI peak represents the degree of variation in NDVI values within each sample region. The FWHM of each sample region is plotted in Figure 16B across the period of observation.

It can be seen in Figure 16A that the average NDVI value for the undamaged region t2u of the test leaf 10, and high NDVI (also undamaged) region c2h of the control leaf 11 shows very little change over the duration of the observation period, falling from approximately 0.58 to approximately 0.54. The FWHM (see Figure 16B) for the same t2u and c2h regions also shows very little change, having a value of 0.07 ± 0.006 throughout the period of observation.

The slight decrease in NDVI exhibited by the t2u and c2h regions can be explained by the prolonged period of darkness in which the experiments are carried out.

Photosynthetic activity decreases during prolonged periods of darkness, therefore some reduction in the NDVI value may be expected.

It can further be seen from Figure 16A that the average NDVI value in the paraquat damaged region t2d of test leaf 10 begins the period of observation at a value of 0.52, slightly below the undamaged regions (t2u and c2h). The NDVI value for region t2d remains at approximately 0.51 for 200 minutes before decreasing by approximately 0.1 in the following 250 minutes. This decrease in NDVI corresponds in time with the increase in damaged leaf area for the test leaf 10 shown between 200 and 450 minutes in Figure 13. After the initial, and significant change in NDVI, a further and more gradual change is seen from 450 to 950 minutes, with the NDVI value falling a further 0.05 in 500 minutes. This more gradual decrease is still a more rapid decrease in NDVI than is observed in the healthy regions (t2u and c2h).

Figure 16B also shows the FWHM for region t2d, which can be seen to undergo a dramatic change between 190 and 330 minutes. The width of the histogram peak can be seen to double in size during this time period, from approximately 0.06 to a peak value of 0.154 at around 330 minutes. After this, the FWHM gradually falls to a value of 0.11 by the end of the observation period.

The broadening of the NDVI histogram peak can be understood in terms of the histogram being constituted of several contributions from different features. Examination of the NDVI maps relating to the region t2d during the time period concerned show the development of several small regions of damage. Initially the damage is not visible at all, resulting in a healthy NDVI profile, the NDVI peak being centred at 0.5. As the experiment progresses, the damage becomes more apparent, with small regions of damage becoming visible within the otherwise healthy region. During this phase, the NDVI histogram will consist of a contribution from the healthy parts of the region, the NDVI peak being centred at 0.5 and also a contribution from the damaged parts of the region, with the damaged parts being centred at a lower NDVI of 0.45.

The broadest NDVI peak at a time of 330 minutes corresponds to the time at which the parts of the region t2d which are damaged encompass approximately half of the entire region t2d, as observed from inspection of the relevant portions of the NDVI maps.

Therefore, at that time, the contribution to the NDVI histogram of the healthy parts and the damaged parts is approximately equal.

As the parts of the region t2d which are damaged expand to encompass the entire region, as can be observed from inspection of the relevant portions of the NDVI maps, the contribution to the NDVI histogram of the healthy parts which were centred at NDVI = 0.5 tends to be diminished until it is no longer present. In this way, the broader peak, with constituent sub-peaks at 0.5 and 0.45 becomes a single narrower peak centred at a lower NDVI value of 0.4 (this single narrower peak representing damaged parts of the region).

It can still further be seen from Figure 16A that the average NDVI value in the bruised region c2b of control leaf 10 begins the period of observation at a value of around 0.52, slightly below the undamaged regions (t2u and c2h). The NDVI value then proceeds to be diminished gradually during the observation period, at a similar rate to the reduction observed in the healthy regions (t2u and c2h).

The FWHM of the region c2b is higher than for the healthy regions, and can be seen in Figure 16B to be relatively constant at around 0.13 for the duration of the observation period. Inspection of the histogram reveals that the NDVI profile for the c2b region consists of a first peak centred at the healthy value of 0.55, and a second stronger peak centred at an NDVI value of approximately 0.5. Further consideration of the relevant NDVI map confirms that a low NDVI part dominates the region c2b, while a normal (healthy) portion of leaf surrounds the low NDVI (bruised) part. Further consideration of the evolution of the NDVI maps of the c2b region during the observation period reveals that the extent of the region c2b which is damaged does not change, leading to a relatively constant average NDVI (Figure 16A) and FWHM (Figure 16B) across the whole observation period.

Once the observation period had ended, a series of images was recorded in order to allow a comparison to be made between the features observable with the NDVI map and those observable from the images to the naked eye. These images were recorded approximately 8 hours after the end of the observation period.

Regarding Figure 17A the regions of damage on test leaf 10 are clearly visible and have expanded further between the end of the observation period and the visual images being recorded. Using this image it is possible to correlate the regions of low NDVI with the regions where the paraquat spray had landed on the plant leaf, confirming the efficacy of the NDVI analysis carried out.

Considering the control leaf 11 shown in Figure 17B, no visible region of damage could be identified on a first inspection of the image. However, the NDVI map shown in Figure 14 clearly identifies a region of low NDVI on control leaf 11, which was investigated as region c2b. Upon closer visual inspection, the low NDVI region could be seen to be caused by a region of bruising to the leaf, whish was likely caused by a physical trauma to the leaf during transport. However, the bruising resulting from the damage was not yet fully developed into a visible mark. While this bruising was just visible to the naked eye, it would likely be missed during all but the closest of inspections, and even then only at the correct angle. However, the region of low NDVI was readily identified by the testing protocol developed and described above.

The use of NDVI images collected over time illustrates the use of a spectral vegetation index to identify and assess regions of a plant specimen which are damaged. It will be appreciated that other forms of damage can be identified and assessed in the same way, and that other forms of spectral vegetation indices may be used as appropriate.

Furthermore, a series of images collected over time can be used to characterise the development or extent of a particular form of damage to a plant specimen in time. However, the techniques used in conjunction with the series of images discussed above can equally be applied to single measurements. For example, previously collected calibration data may enable a single NDVI map and histogram taken of a plant specimen to be compared with the calibration data and used to identify regions which exhibit either abnormal NDVI values or distributions of NDVI values (the distributions may for example be full width half-maximum values).

It will be appreciated that while some forms of plant damage, such as drought, might affect an entire specimen, other forms of damage, such as physical damage from a pest eating parts of a leaf, or burrowing insects, would show localised damage.

Furthermore, some forms of fungus pathogens, such as powdery mildew produces a films over the entire leaf, affecting the reflectance over a large area, while some infections cause localised lesions to a leaf.

The identification of regions of leaf damage within an otherwise healthy leaf, or the confirmation that all parts of a leaf are similarly affected, allows particular pathogens to the identified and dealt with accordingly.

Embodiments of the invention may be suitable for applications such as monitoring other observable characteristics of a crop (phenotyping). For example, the ratio of reflectances at specific wavelengths may be used to indicate the ripeness of a crop. In some crops, the ripeness is difficult to gauge visually, for example in soft fruits such as tomatoes, dark grapes or sweet peppers or the like. Plant health and ripeness may be considered to be examples of plant characteristics.

An indication of phenotype may be used in combination with a series of images taken over time (chronological images) to monitor the ripening process in a crop. Furthermore, the use of images, rather than single measurements, enables the observance of non-uniform ripening or phenotype within a crop. Such techniques may be applied to a crop or to an individual plant or part of plant, such as, for example, an individual fruit.

Examples of the use of spectral data to aid with plant phenotyping can be found in:

Bettina Berger, Boris Parent and Mark Tester, “High-throughput shoot imaging to study drought responses”, Journal of Experimental Botany, Vol. 61, No. 13 pages 3519-3528, 2010;

Laury Chaerle, Ilkka Leinonen, Hamlyn G. Jones and Dominique Van Der Straeten, “Monitoring and screening plant populations with combined thermal and chlorophyll fluorescence imaging” Jornal of Experimental Botany, Vol. 58, No. 4, pages 773-784, 2007; and

Rana Munns, Richard A. James, Xavier R. R. Sirault, Robert T. Furbank and Hamlyn G. Jones, “New phenotyping methods for screening wheat and barley for beneficial responses to water deficit” Journal of Experimental Botany, Vol. 61, No. 13, pages 3499-3507, 2010;

which are hereby incorporated by reference.

It will be appreciated that in addition to or instead of NDVI or PRI, alternative spectral vegetative indices may be used.

An embodiment of the invention may be configured to calculate a Carter Index II, which measures reflectance at 695 nm and 760 nm. The Carter Index II is calculated according to the following equation:

$$\text{Carter Index II} = \frac{R_{695}}{R_{760}} \qquad (4)$$

where:

R_{695} is the reflectance at 695 nm, and
R_{760} is the reflectance at 760 nm.

Further details of the Carter Index II can be found in Gregory A Carter, William G Cibula, and Tommy R Dell, “Spectral reflectance characteristics and digital imagery of a pine needle blight in the southeastern United States", Canadian Journal of Forest Research 26.3 (1996), pages 402-407.

An embodiment of the invention may be configured to calculate a Lichtenthaler Index I, which measures reflectance at 800 nm and 680 nm. The Lichtenthaler Index I is calculated according to the following equation:

$$\text{Lichtenthaler Index I} = \frac{R_{800} - R_{680}}{R_{800} + R_{680}} \qquad (4)$$

where:

R_{800} is the reflectance at 800 nm, and
R_{680} is the reflectance at 680 nm.

Further details of the Lichenthaler Index I can be found in H K Lichtenthaler, M Lang, M Sowinska, F Heisel, and J A Miehe, “Detection of Vegetation Stress Via a New High Resolution Fluorescence Imaging System", Journal of Plant Physiology 148.5 (1996), pages 599-612.

An embodiment of the invention may be configured to calculate the Optimized Soil-Adjusted Vegetation Index (OSAVI), which measures reflectance at 800 nm and 670 nm. The OSAVI value is calculated according to the following equation:

$$OSAVI = (1 + 0.16)\left(\frac{R_{800} - R_{670}}{R_{800} + R_{670} + 0.16}\right) \qquad (4)$$

where:

R$_{800}$ is the reflectance at 800 nm, and
R$_{670}$ is the reflectance at 670 nm.

Further details of OSAVI can be found in Genevieve Rondeaux, Michael Steven, and Frederic Baret. “Optimization of soil-adjusted vegetation indices", Remote Sensing of Environment 55.2 (1996), pages 95-107.

An embodiment of the invention may be configured to calculate a Simple Ratio Pigment Index (SRPI), which measures reflectance at 430 nm and 680 nm. SRPI is calculated according to the following equation:

$$SRPI = \frac{R_{430}}{R_{680}} \qquad (4)$$

where:

R$_{430}$ is the reflectance at 430 nm, and
R$_{680}$ is the reflectance at 680 nm.

Further details of SRPI can be found in George Alan Blackburn, “Relationships between Spectral Reflectance and Pigment Concentrations in Stacks of Deciduous Broadleaves", Remote Sensing of Environment 70.2 (Nov. 1999), pages 224-237.

An embodiment of the invention may be configured to calculate a Water Index (WI), which measures reflectance at 970 nm and 900 nm. WI is calculated according to the following equation:

$$WI = \frac{R_{970}}{R_{900}} \qquad (4)$$

where:

R_{970} is the reflectance at 970 nm, and
R_{900} is the reflectance at 900 nm.

Further details of WI can be found in J Penuelas, J Pinol, R Ogaya, and I Filella, “Estimation of plant water concentration by the reflectance Water Index WI (R900/R970)", International Journal of Remote Sensing 18.13 (1997), pages 2869-2875.

An embodiment of the invention may be configured to calculate an alternative Photochemical Reflectance Index (PRI), which measures reflectance at 571 nm and 531 nm (as opposed to 571 nm and 541 nm. The alternative PRI is calculated according to the following equation:

$$PRI = \frac{R_{571} - R_{531}}{R_{571} + R_{531}} \qquad (2)$$

where:

R_{531} is the reflectance at 531 nm, and
R_{571} is the reflectance at 571 nm.

Further details of the alternative PRI can be found in J A Gamon, L Serrano, and J S Surfus, “The Photochemical Reflectance Index: An Optical Indicator of Photosynthetic Radiation Use Efficiency across Species, Functional Types, and Nutrient Levels", Oecologia 112.4 (1997), pp. 492-501.

An embodiment of the invention may be configured to calculate a Pigment Specific Simple Ratio (PSSR). A PSSR may take the form of an index which measures reflectance at 800 nm and 680 nm (PSSRa). Alternatively, PSSR may take the form of an index which measures reflectance at 800 nm and 635 nm (PSSRb). PSSRa and PSSRb are calculated according to the following equations:

$$PSSRa = \frac{R_{800}}{R_{680}}, \quad PSSRb = \frac{R_{800}}{R_{635}} \qquad (4), (5)$$

where:

R_{800} is the reflectance at 800 nm,
R_{680} is the reflectance at 680 nm, and

R_{635} is the reflectance at 635 nm.

Further details of PSSRa and PSSRb can be found in George Alan Blackburn, “Relationships between Spectral Reflectance and Pigment Concentrations in Stacks of Deciduous Broadleaves", Remote Sensing of Environment 70.2 (Nov. 1999), pages 224-237.

An embodiment of the invention may be configured to calculate the Red-Edge Position (REP), which measures reflectance at 670 nm, 700 nm, 740 nm and 780 nm. The REP is calculated according to the following equation:

$$REP = 700 + 40 \times \left(\frac{\frac{R_{670} + R_{780}}{2} - R_{700}}{R_{740} - R_{700}} \right) \qquad (4)$$

where:

R_{670} is the reflectance at 670 nm,
R_{700} is the reflectance at 700 nm,
R_{740} is the reflectance at 740 nm, and
R_{780} is the reflectance at 780 nm.

Further details of the REP can be found in Jan G P W Clevers, Steven M de Jong, Gerrit F Epema, Freek van der Meer, Wim H Bakker, Andrew K Skidmore, and Elisabeth A Addink, “MERIS and the red-edge position", International Journal of Applied Earth Observation and Geoinformation 3.4 (2001), pages 313-320.

An embodiment of the invention may be configured to calculate a Structure-Insensitive Pigment Index (SIPI), which measures reflectance at 800 nm and 445 nm. The SIPI value is calculated according to the following equation:

$$SIPI = \frac{R_{800} - R_{445}}{R_{800} + R_{445}} \qquad (2)$$

where:

R_{800} is the reflectance at 800 nm, and
R_{445} is the reflectance at 445 nm.

Further details of SIPI can be found in J Penuelas and Yoshio Inoue, “Reflectance indices indicative of changes in water and pigment contents of peanut and wheat leaves", Photosynthetica (1999), Volume 36, Issue 3, pp 355-360.

Experimental studies described above focus on the use of maize and tomato plants. Maize is of particular interest as an example of a high value commercial crop. Tomatoes, on the other hand, present an example of a high value horticultural crop. In addition, water stress in tomatoes has been studied using prior art techniques and systems. Tomatoes therefore provide a reliable crop with which to verify the use of embodiments of the invention.

It will be appreciated that embodiments of the invention may be applied to alternative species of plant. The health (or other characteristic) of any green leafed plant may be assessed with embodiments of the invention.

In addition to the use of hyperspectral imaging for the observation of spectral vegetative indices for pathogen identification, embodiments of the invention may be applied to healthy crops.

It will be appreciated that aspects of the present invention can be implemented in any convenient way including by way of suitable hardware and/or software. For example, a device arranged to implement the invention may be created using appropriate hardware components. Alternatively, a programmable device may be programmed to implement embodiments of the invention. The invention therefore also provides suitable computer programs for implementing aspects of the invention. Such computer programs can be carried on suitable carrier media including tangible carrier media (e.g. hard disks, CD ROMs and so on) and intangible carrier media such as communications signals.

CLAIMS:

1. A plant characteristic measurement system comprising:

a first radiation source configured to emit radiation at a first radiation wavelength and a second radiation source configured to emit radiation at a second radiation wavelength,

a detector configured to detect radiation at the first radiation wavelength and at the second radiation wavelength, the detector comprising a two-dimensional imaging array,

a controller configured to control the first and second radiation sources and the detector to detect radiation reflected by the a plant specimen when it is irradiated by the first and second radiation sources at the first and second radiation wavelengths, and

a processor configured to calculate an indicator of the plant characteristic based upon detected images of radiation reflected by the plant specimen at each of the first and second radiation wavelengths.

2. A plant characteristic measurement system according to claim 1 wherein the indicator of the plant characteristic is a two-dimensional array of plant characteristic indicator values.

3. A plant characteristic measurement system according to claim 1 or claim 2 wherein the indicator of the plant characteristic is a spectral vegetation index.

4. A plant characteristic measurement system according to claim 3 wherein the spectral vegetation index is Normalised Difference Vegetation Index or Photochemical Reflectance Index.

5. A plant characteristic measurement system according to any preceding claim wherein the first and the second radiation sources comprise light emitting diodes or laser diodes.

6. A plant characteristic measurement system according to any preceding claim wherein the first radiation source, the second radiation source, the detector, the controller and the processor are arranged as a single unit.

7. A plant characteristic measurement system according to claim 6 wherein the single unit is a handheld device.

8. A plant characteristic measurement system according to any one of claims 1 to 5, further comprising a first device and a detachable module wherein the detector forms part of the first device and wherein the first radiation source and the second radiation source form part of the detachable module.

9. A plant characteristic measurement system according to claim 8 wherein the first device is a mobile telephone, a digital camera or a tablet computer.

10. A plant characteristic measurement system according to claim 8 or claim 9 wherein the processor is within the first device.

11. A plant characteristic measurement system according to any preceding claim wherein the controller is arranged to cause the plant characteristic measurement system to irradiate the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and to detect a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength, and to calculate an indicator of the plant characteristic based upon the plurality of detected images.

12. A plant characteristic measurement system according to any one of claims 1 to 10 wherein the controller is arranged to cause the plant characteristic measurement system to irradiate the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and to detect a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength, and to calculate a plurality of indicators of the plant characteristic based upon the plurality of detected images.

13. A plant characteristic measurement system according to claim 12 wherein the plurality of images is a temporal sequence of images with a predetermined separation in time.

14. A plant characteristic measurement system according to any preceding claim wherein the plant characteristic is plant health or ripeness.

15. A method of measuring a characteristic of a plant specimen, the method comprising:

irradiating the plant specimen with radiation at a first radiation wavelength,

detecting an image of radiation reflected by the plant specimen at the first radiation wavelength,

irradiating the plant specimen with radiation at a second radiation wavelength,

detecting an image of radiation reflected by the plant specimen at the second radiation wavelength, and

calculating an indicator of the plant characteristic based upon the detected images.

16. A method of measuring the characteristic of a plant specimen according to claim 15 wherein the indicator of the plant characteristic is a two-dimensional array of plant characteristic indicator values.

17. A method of measuring the characteristic of a plant specimen according to claim 15 or claim 16 wherein the indicator of the plant characteristic is a spectral vegetation index.

18. A method of measuring the characteristic of a plant specimen according claim 19 wherein the spectral vegetation index is Normalised Difference Vegetation Index or Photochemical Reflectance Index.

19. A method of measuring the characteristic of a plant specimen according to any one of claims 15 to 18 further comprising comparing the indicator of the plant characteristic with a threshold value.

20. A method of measuring the characteristic of a plant specimen according to any one of claims 15 to 19 the method further comprising irradiating the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and detecting a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength, and

calculating an indicator of the plant characteristic based upon the plurality of detected images.

21. A method of measuring the characteristic of a plant specimen according to any one of claims 15 to 19 the method further comprising irradiating the plant specimen a plurality of times at the first radiation wavelength and a plurality of times at the second radiation wavelength, and detecting a plurality of images of radiation reflected by the plant at the first radiation wavelength and at the second radiation wavelength and calculating a respective plurality of indicators of the plant characteristic based upon the plurality of detected images.

22. A method of measuring the characteristic of a plant specimen according to claim 21 wherein the plurality of images is a temporal sequence of images with a predetermined separation in time.

23. A computer program comprising computer readable instructions configured to cause a computer to carry out a method according to any one of claims 15 to 22.

ABSTRACT:

A plant characteristic measurement system comprising, a first radiation source configured to emit radiation at a first radiation wavelength and a second radiation source configured to emit radiation at a second radiation wavelength, a detector configured to detect radiation at the first radiation wavelength and at the second radiation wavelength, the detector comprising a two-dimensional imaging array, a controller configured to control the first and second radiation sources and the detector to detect radiation reflected by the a plant specimen when it is irradiated by the first and second radiation sources at the first and second radiation wavelengths, and a processor configured to calculate an indicator of the plant characteristic based upon detected images of radiation reflected by the plant specimen at each of the first and second radiation wavelengths.

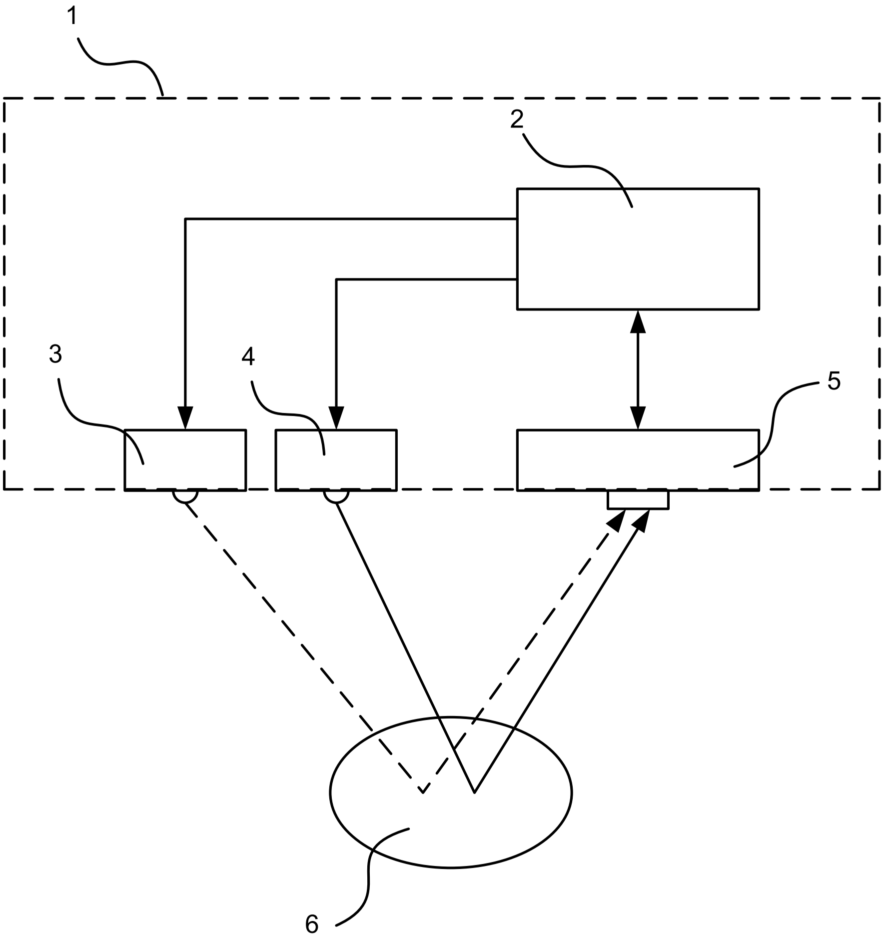

FIG 1

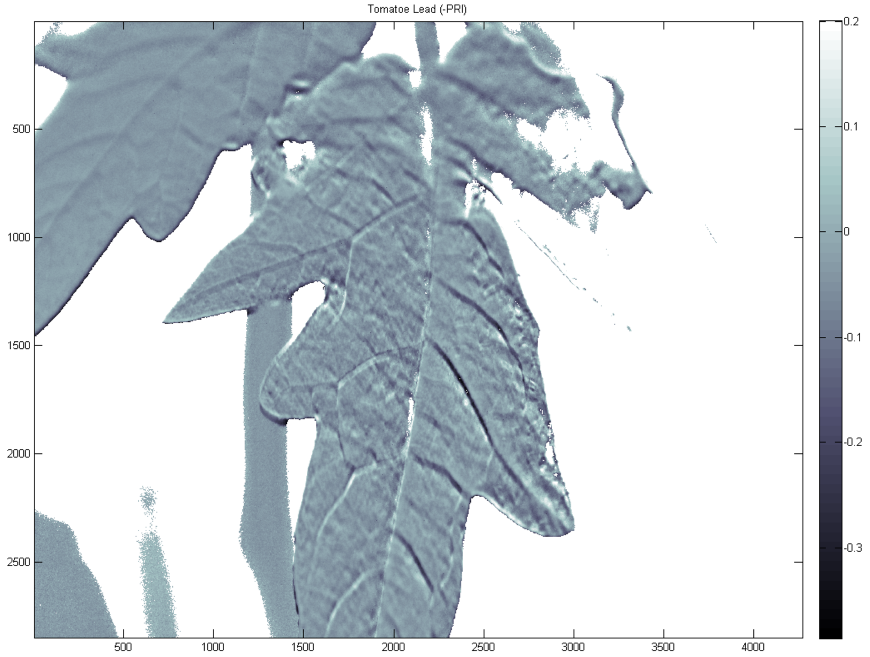
Tomatoe Lead (-PRI)
500
1000
1500
2000
2500
500
1000
1500
2000
2500
3000
3500
4000
0.2
0.1
0
-0.1
-0.2
-0.3

FIG 2

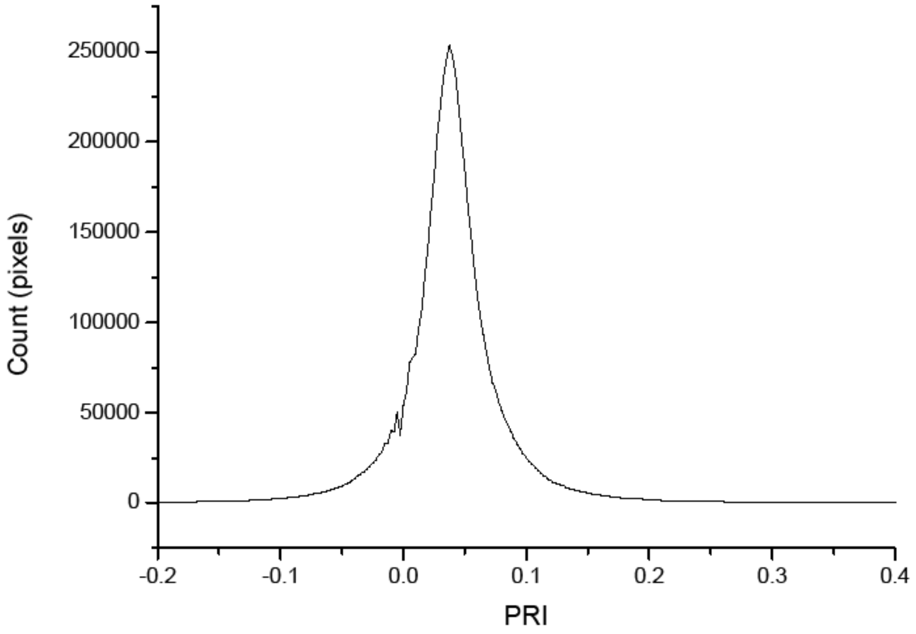
250000
200000
150000
100000
50000
0
Count (pixels)
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
PRI

FIG 3

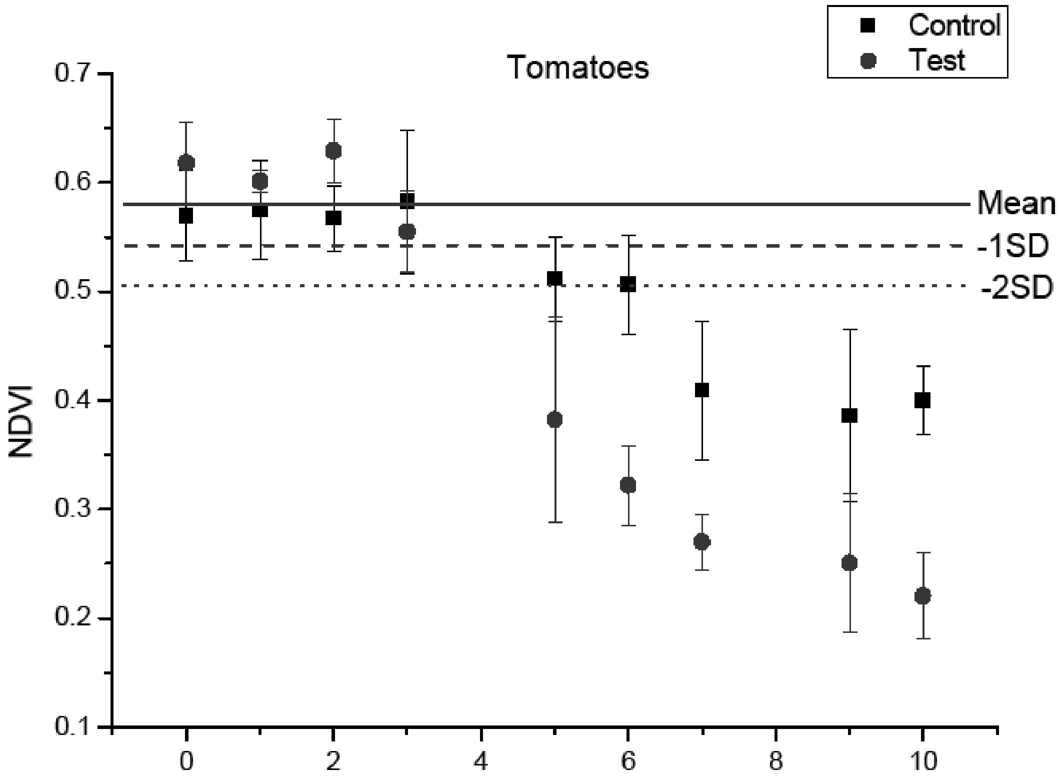
Control
Test
Tomatoes
0.7
0.6
0.5
0.4
0.3
0.2
0.1
NDVI
Mean
-1SD
-2SD
0
2
4
6
8
10

FIG 4

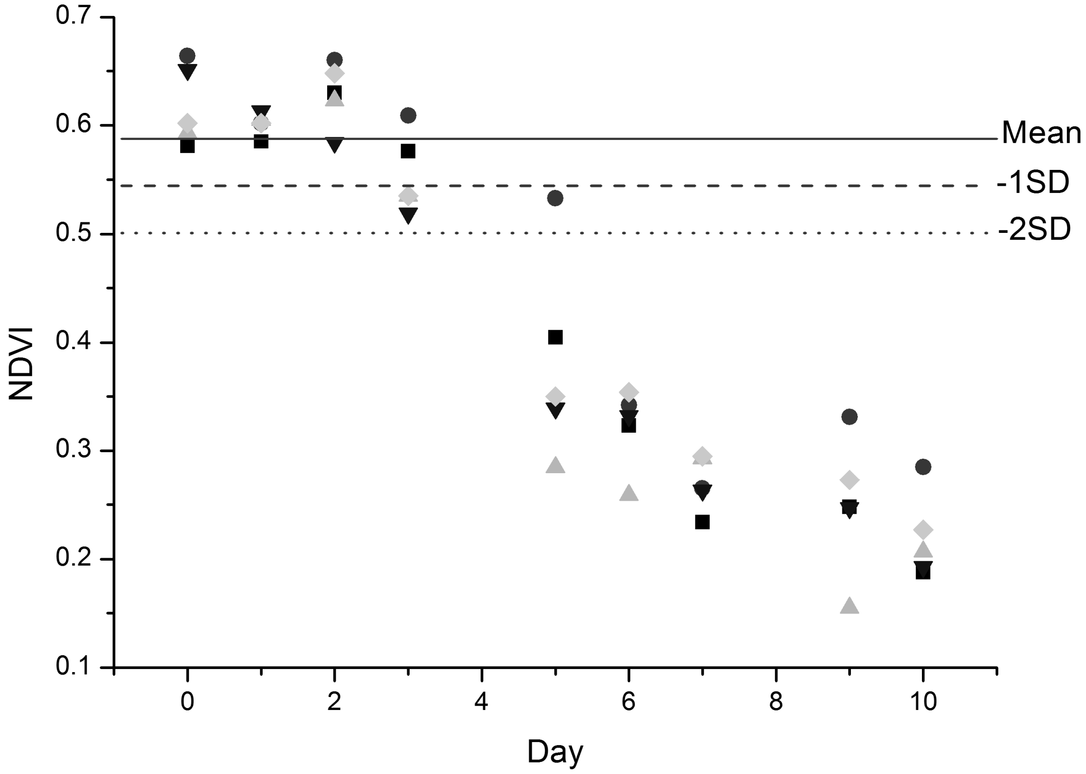
0.7
0.6
0.5
0.4
0.3
0.2
0.1
NDVI
Mean
-1SD
-2SD
0
2
4
6
8
10
Day

FIG 5

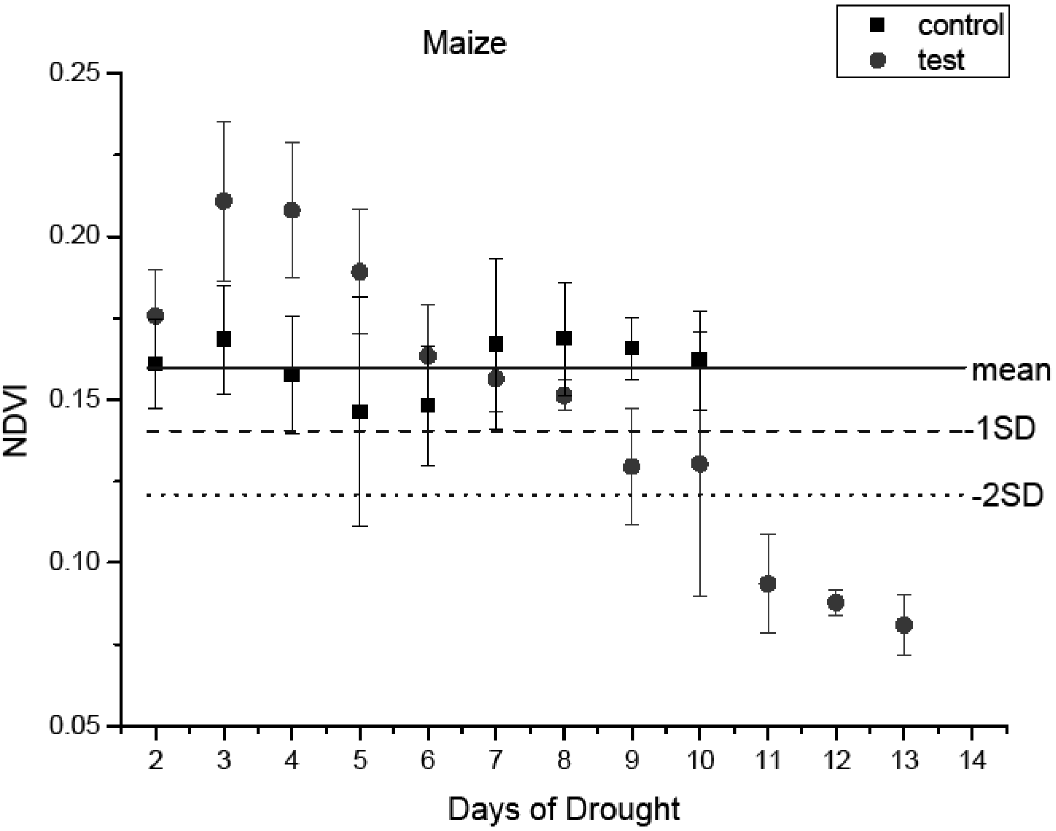
Maize
■ control
● test
0.25
0.20
0.15
0.10
0.05
NDVI
mean
-1SD
-2SD
2
3
4
5
6
7
8
9
10
11
12
13
14
Days of Drought

FIG 6

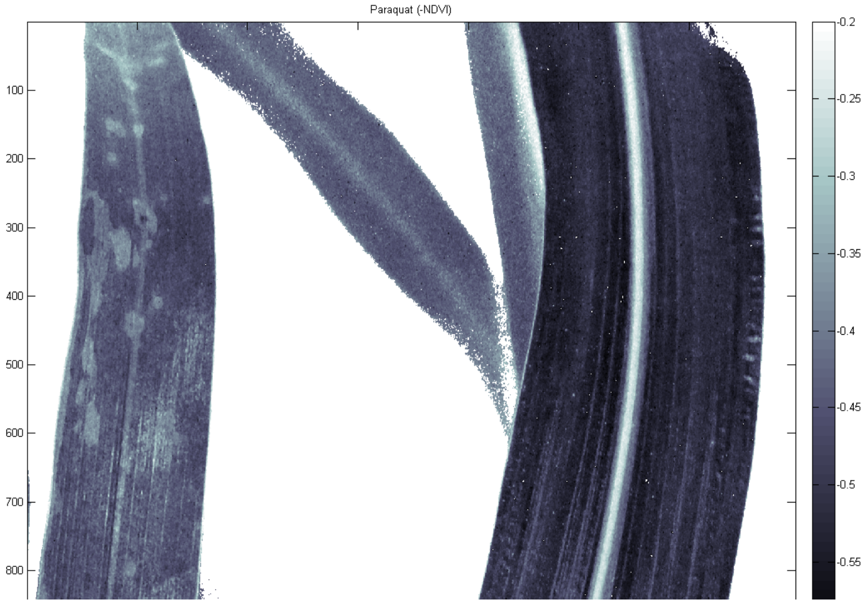
Paraquat (-NDVI)
100
200
300
400
500
600
700
800
-0.2
-0.25
-0.3
-0.35
-0.4
-0.45
-0.5
-0.55

FIG 7

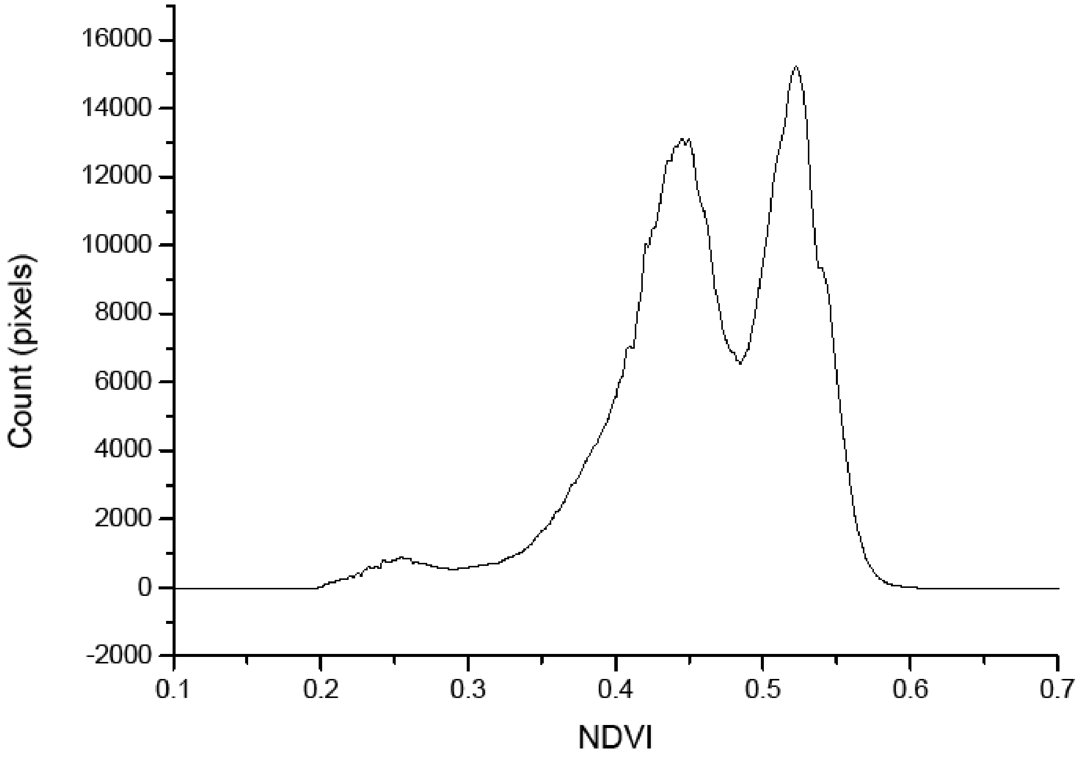
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
Count (pixels)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
NDVI

FIG 8

FIG 9

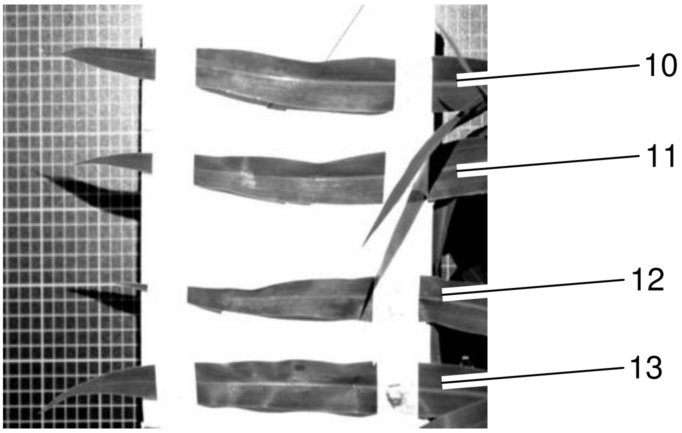

FIG 10A

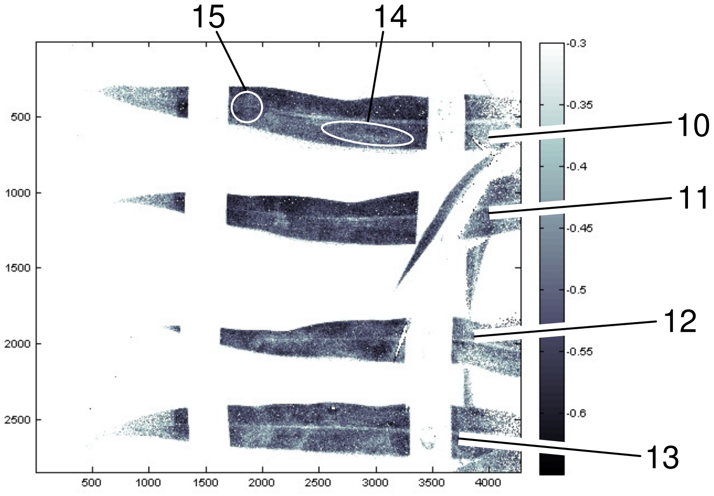

FIG 10B

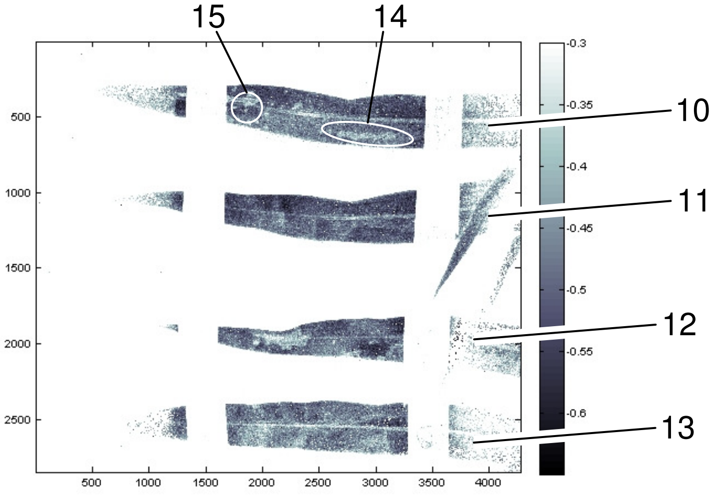

FIG 11

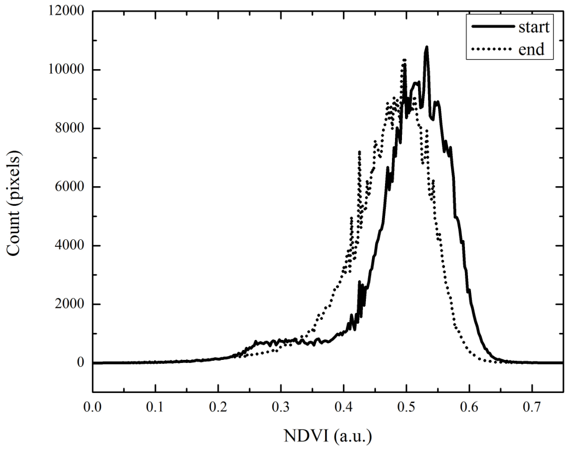

FIG 12A

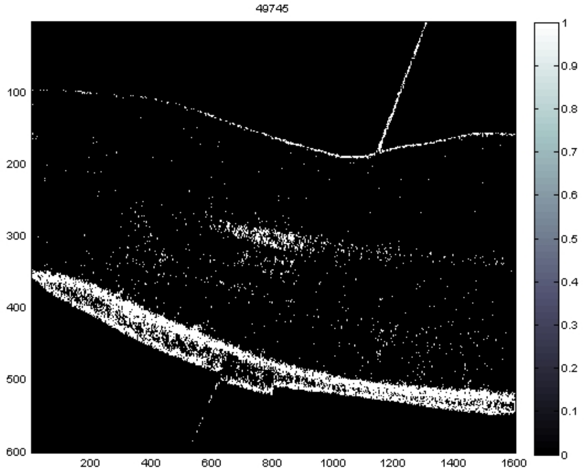

FIG 12B

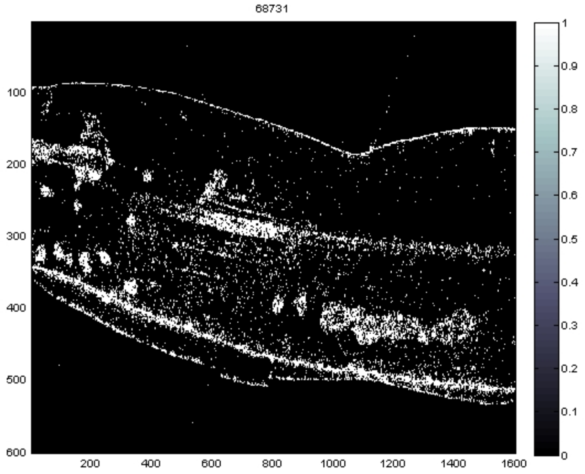

FIG 13

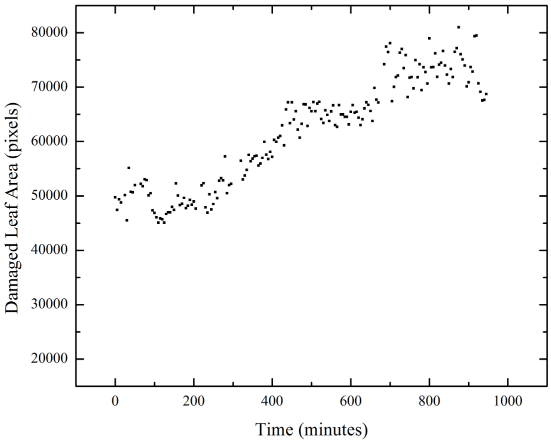

FIG 14

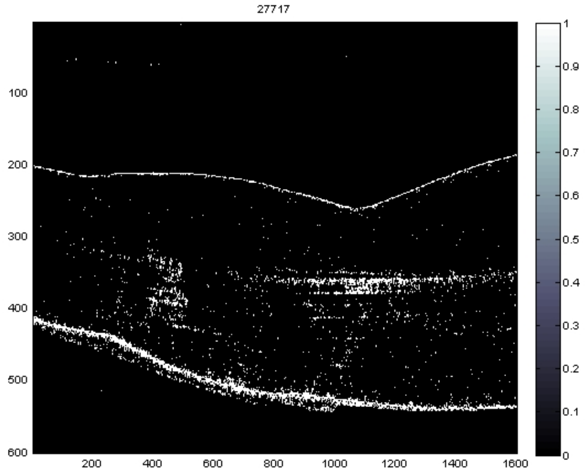

FIG 15

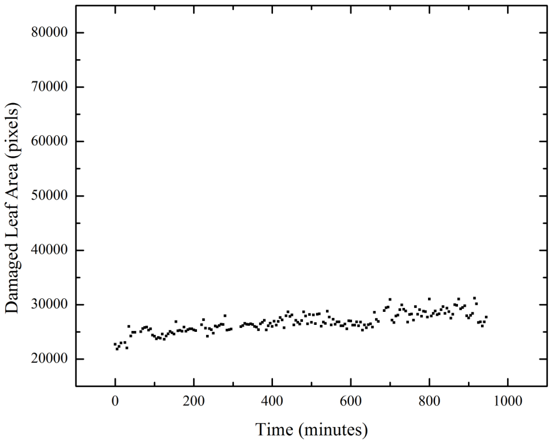

FIG 16A

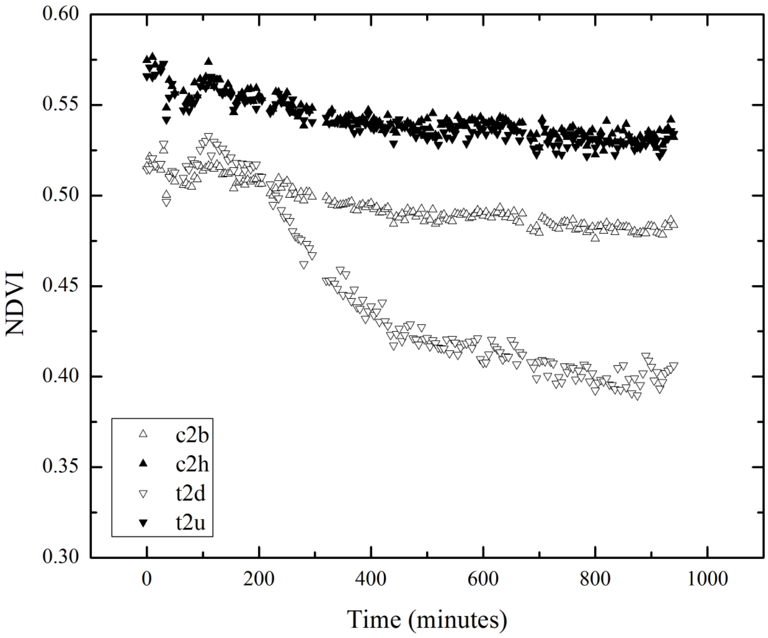

FIG 16B

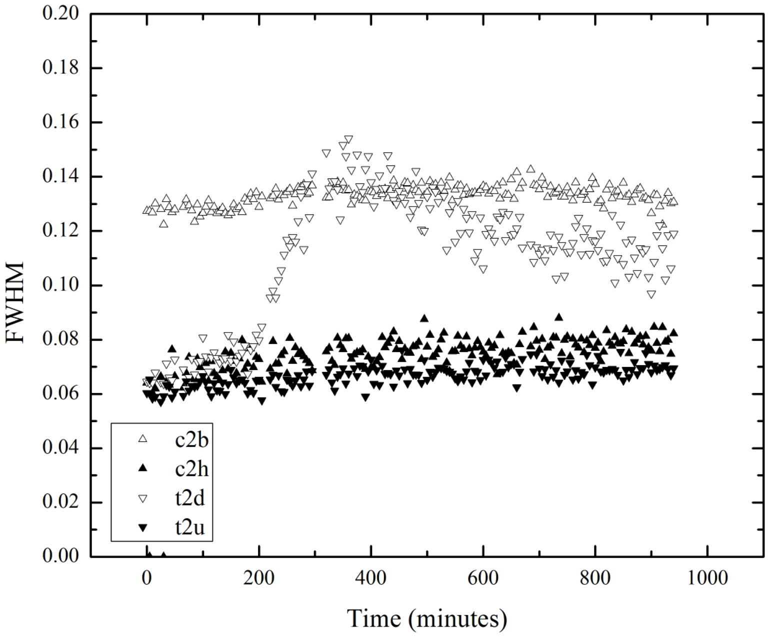

FIG 17A

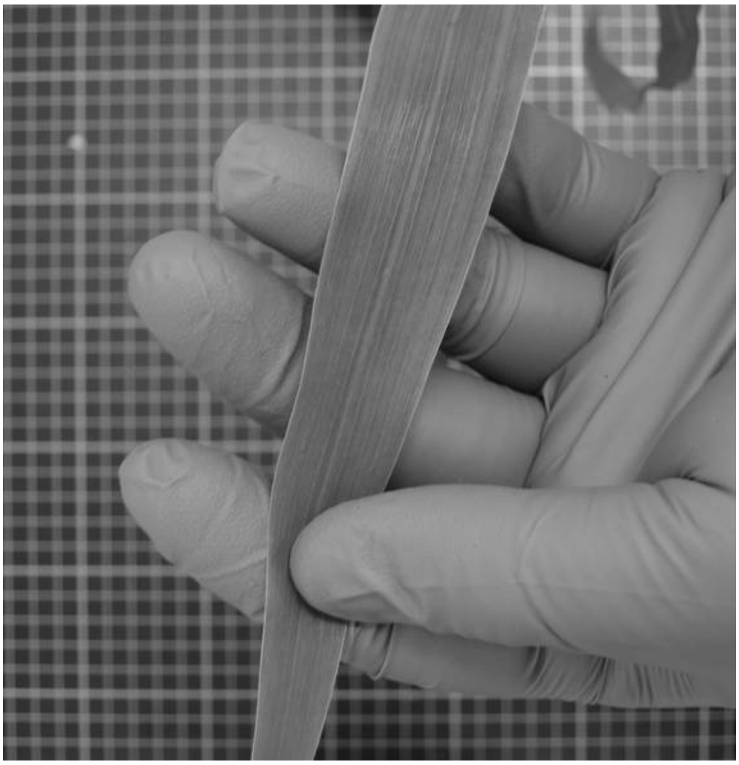

FIG 17B